Study of Position Resolution with COPS

J. Moromisato[1], E. von Goeler, S. Reucroft
Northeastern University

D. Eartly, T. Droege, D. Prokofiev
Fermi National Accelerator Laboratory

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ABSTRACT

We describe an optical beam sensing device that can measure transverse displacements with accuracy of a few microns. An analog readout prototype with a set of four linear CCD arrays arranged around a square aperture, and illuminated by a cross-hair laser, was built and tested by the authors. Performance tests results demonstrate a linearity better than five microns throughout an active transverse range of over 20mm. The reproducibility of the measurements was better than 2 μm. Long term stability is 5 μm.

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[1] Corresponding Author. Tel. (617) 373-2939, Fax . (617) 373-2943, e-mail jhm@neu.edu

Introduction.

New detectors for the Large Hadron Collider (LHC) require position monitoring of large scale equipment with a precision in the range of 10 – 100 μm. Monitoring strings of large detector components is complicated by the fact that most optical positioning devices interact with or interrupt the reference laser line. The non-refractive 'transparent' sensor discussed here allows independent position measurements. The CCD Optical Position Sensor (COPS) was designed at Fermilab with that feature in mind: it intercepts only the outer part of the reference laser beam, while the core continues, to be again partially intercepted by the next COPS. Several COPS, positioned along the same line, can be located very precisely and independently with respect to a single laser beam.

The COPS uses commercial linear CCD arrays. They are intended for use in the position monitoring of the cathode strip chambers in the Endcap Muon detector of CMS.

The results presented here were obtained with an early prototype of COPS[1], and constitute a detailed resolution and stability study. Work is continuing towards building and testing a new design with onboard DSP (digital signal processor), to allow for faster response and simpler computer readout.

System Description

The CCD Optical Position Sensor (COPS) consists of four linear CCD arrays, arranged around a square opening on a printed circuit board[2] (Figure 1). A cross-hair laser defines a known direction and orientation in space. The cross-hair is detected by the four linear arrays on the COPS board, allowing the precise determination of the X-Y position of the laser axis at the COPS plane. The square opening, or window, on the prototype board has dimensions of 3.4 x 3.4 cm^2. It allows the laser beam to continue on to the next COPS. This 'total' transparency is an important feature of the COPS: the beam can be detected by all the COPS along the same line without being disturbed by them.

The Linear CCD Arrays

The linear CCD arrays[2] were designed for use in facsimile, image scanner, and OCR devices. The array consisted of 2048 pixels, each 14 μm x 14 μm of sensitive surface, with negligible inter-pixel spacing. The active range of the arrays is 28.67mm. A set of four CCD arrays were inserted into corresponding sockets, around the square window cut near the center of the board.

[2] SONY-ILX503A, on a 22 pin DIP. Produced by Sony Corp.

Circuit Board And Computer Interface

Each CCD has a signal amplifier, built-in timing generator and clock drivers, with a max clock frequency of 5MHz. The output lines from the four CCD arrays are multiplexed into a 16 bit ADC, also provided with calibration inputs. The board includes control and interface circuits to a byte wide interface board in a dedicated personal computer (PC). The PC interface board signals the shift of charge (from CCD sensitive area) to the transfer shift register, and initiates sampling of charge, multiplexing, ADC conversion, and two-byte readout by the PC I/O bus.

The Cross-hair Laser

For these tests we used a Lasiris[3] cross-hair laser diode module with wavelength of 670nm, a five-degree fan-out angle, and approximately uniform line intensity which proved adequate over our 6m test range. In long-range tests, we intend to use a more conventional cross-hair laser source, with cylindrical lens setup to produce a Gaussian intensity in two perpendicular lines. This will mitigate the reduction in the power density of the beam versus source distance, which could limit long beam path operations of the COPS.

Apparatus Setup and Operation

All tests were performed on an optical bench, in a darkroom especially set up at Northeastern University. The ceiling lights were normally on, except for some measurements and background checks. A XY micrometric stage, to which the COPS board was attached, was normally fixed to the table, while the laser source stand was moved along the table to change the source-sensor distance. The data was collected with a generic 586-133 MHz personal computer, using in-house software.

The Need for Absorbers

The linear CCD arrays are very sensitive and room light will saturate them completely. The light exposure of the CCD arrays can, in principle, be controlled by the speed of the readout cycle, but in our case this was limited by the processing speed of the computer and the data transfer rate. A single readout cycle, that is the time needed to clear all four CCDs, read and digitize the data, and calculate the peak positions, was determined to be less than 2/3 sec.

For practical applications, the CCD arrays need to be covered with some kind of absorber in order to detect the desired laser signal with room light present. Most absorbers are too weak: for instance, red vinyl tape can only be used under almost complete room darkness. Some metallic films have the right absorption but they are not uniform[4]. We performed our initial linearity tests using gold coated (by sputtering) CCD arrays; however the absorption was somewhat irregular and relatively large deviation from linearity were observed.

We have tested commercial vinyl adhesive tapes[5] of different colors and found at least one (brown, 3M 054007-10885) with the right absorption properties. The color

[3] SNF-501H-6705-10-5, from Lasiris Inc, St. Laurent, Quebec, Canada (514) 335-1005
[4] Even thick metallic films (about 100nm thick) suffer from pin holes and uneven absorption properties.
[5] Vinyl electrical tape from 3M Co. Sales: McMaster-Carr, New Brunswick, NJ, (908) 329-3200

of the tape is strongly correlated with its opacity to ambient light and we found that the brown tape absorbed most of the ambient light while allowing a good fraction of the laser light to pass through.

All measurements reported here were performed under normal room illumination (except that the walls were painted black). One strip of brown electrical tape was used as absorber over each of the CCD arrays. For most of the measurements, not including the linearity checks, the COPS had a black cardboard hood to avoid direct exposure to the ceiling lights. Some basic measurements, such as the spectral properties of the vinyl tape, or the effect of aging and/or radiation, have not been performed as yet. The extent of the spatial non-uniformity of the tape have been implicitly measured in our tests. For example, in the linearity tests the laser beams scanned over 20 mm of the length of the tapes with very small changes in the position resolution.

The Laser Beam Intensity

The cross-hair laser had a variable intensity beam with a 5 degrees divergence. The distance between the laser and the COPS was varied, from a fraction of one meter to more than the full length of the optical bench (8m). The intensity of the cross-hair laser has to be regulated as well, to avoid saturating the CCDs. This presents a challenge when multiple COPS are used, because the cross-hair intensity per pixel will decrease with the distance of the laser to the sensors. The nearest CCD sensors may saturate, while the farthest ones might not see a clear line. This can be dealt with in three different ways:

1) by using a variable output laser, which can be computer controlled (the Lasiris output can be modulated). Each sensor, then, could be read only when the laser intensity is appropriate for it, or,

2) by using different absorbers on the different COPS, or,

3) by using cylindrical lens optics to generate a cross-hair pattern which produces a Gaussian line intensity distribution.

For all our measurements, the cross-hair laser intensity was set manually. There is an asymmetry in the generation of the two orthogonal lines in the cross-hair pattern. One of them is slightly sharper, better focussed, than the other. Since the positions of the two arms are independent of each other, the asymmetry in their shape has no effect on the operation of the COPS. When the laser intensity changes with time, a variation of the position determination can be observed under certain condition as described below.

Peak Finder Algorithm

Each CCD detects one of the four arms of the cross-hair laser. The resulting spectra are relatively simple ones. Typical CCD spectra can seen Figure 2b, which shows a clear peak over a slowly rising background. The width of the peak corresponds to the thickness of the crosshair line, and depends on the separation between CCD sensors and the laser source. It varies from one hundred to several hundred pixels. The peak position can be determined with high statistical precision and reproducibility of 1/10 of a pixel or better.

The background has two sources: the device dark current and the background illumination. The dark current increases with the pixel address, from a few counts to about 200 counts (Figure 2a). The effect of background illumination is to add a constant count, regardless of pixel address. The difference in behavior, of the two backgrounds, is a feature of the particular CCD we used. The rising slope in the dark current spectra is due to the presence of noise and leakage current as the charge signal is shifted from channel to channel in the shift register. The background illumination does not show similar behavior because the photodiodes charge is transferred to the shift registers all at once. Since the saturation point of the CCDs is above 6000 ADC counts, the signal to noise ratio is comfortably high.

The background subtracted CCD spectra, as in Figure 2c, show the presence of smooth and long tails. The extracted signal spectra, as in Figure 2d, are the background-subtracted spectra with a constant offset (arbitrarily set to 300 ADC counts) and zero negatives. In most later analysis the offset was calculated in a different way: it was defined as the peak height minus 20 times its square-root. This reduced the sensitivity to the laser beam intensity fluctuations mentioned above.

The peak position in the signal spectrum is defined simply as the weighted mean of all the pixels. Gaussian fits that were tried for comparison add very little to the accuracy of the simple peak finding algorithm.

Linearity Measurements

To test the linearity of the system, the COPS was attached to an X-Y micrometer stage, and the cross-hair laser was located 1 m away. Ten peak readings were taken at each position of the micrometer stage, and the average of those readings was then plotted against the stage displacement (Figure 3a). The deviation from linearity, Figure 3b, shows a rms of about 5μm throughout the whole sensitive range. The orthogonal sensors, i.e. the CCDs measuring the non varying dimension (see Figure 3c), give an indication of the small rotations undergone by the micro-stage. Those fluctuations are unrelated to the COPS performance, and should be properly taken into account when estimating the COPS resolution.

Position Resolution

COPS measures very accurately the displacement of the CCD sensors in a plane perpendicular to the laser beam. The smooth distribution of the deviation from linearity, mentioned above, is an indication of the precision and accuracy with which one can determine a position. Since only one COPS prototype was available for our studies, we were not able to determine its intrinsic resolution (for instance, by tracking the laser beam through several COPS). The main external effect comes from non-rigidity of the COPS-laser diode system as a whole. Small oscillations, mainly of the laser diode, translated into noticeable movements of the cross-hair beam. However, by taking some measurements with the laser diode very close to the COPS, one can obtain an upper limit of the COPS resolution of about 2 μm.

Sensitivity to Axial Rotations

A 2-dimensional position sensor will normally supply the values of two orthogonal coordinates, thus defining the position of the point at their intersection. The angular orientation of such measuring device must be known, i.e. must be determined beforehand, otherwise the position determination will be in error. A COPS can be operated with only two CCD arrays, covering two orthogonal directions. The only difference with other 2-D position sensors is that, with this simplified COPS, the orientation of the cross-hair pattern must also be determined beforehand. The use of four CCD arrays gives COPS not only a high degree of redundancy, but a capability to measure axial rotations as well. A rotation about the laser beam axis will be measured independently by the two pairs of CCD arrays. Given the spacing between the arrays, and the CCD resolution, we can expect an axial rotation determination better than 0.1 mrad.

Range of Measurements

There is a minimum and a maximum distance between the laser source and the COPS, for satisfactory operation. The minimum distance is determined by the laser beam divergence. For instance, the laser we used has a divergence of 5 degrees (~0.09 radians). If the spacing between a pair of CCD arrays, on opposite sides of the cutout window, is 45 mm, then a minimum distance of 0.5 m is required to fully illuminate the sensors. If a 20-mm dynamic range is desired the minimum distance goes up to 0.72 m. The maximum range is limited by the optical characteristics of the cross-hair generator, and by the laser intensity. Since the line width of the cross-hair pattern increases with the range, a point will be reached when it becomes as large as the length of the CCD array, and no meaningful reading of the position could be performed.

We have tested our COPS prototype up to a distance of 13.6m (see beam profile in Figure 4), using the Lasiris laser. In order to achieve such distance, in excess of our darkroom dimensions, we used a mirror to reflect the laser beam. Even though the beam profile is about 1000 pixels wide, including the wings, the offset signal on which the peak position is determined, is much narrower. One can still obtain dynamic ranges over 20mm. Given that the cross-hair generator and the optics provided with the laser diode were of standard grade, we believe that specially built lasers can increase the COPS operational range by a substantial factor. For instance, better focussing in the cross-hair generator would go a long ways toward extending the COPS' operational range. Another option would to use two independent line generators, oriented at right angles, instead of a cross-hair generator. The line generator optics are not only simpler, and much less expensive, but can be adjusted to produce lines that are sharper than those from cross-hair generators.

Stability Checks

Because of the pixellated nature of the sensors, the stability of the position measurement is quite good. For instance, temperature effects are almost negligible; they only cause sub-micron dimensional changes in the arrays themselves and in their supports. There is also a temperature effect on the dark current (about a 10% increase per degree C), but that has a negligible effect on the peak position, due to the high signal to noise ratio mentioned above.

Long term exposure and other tests were performed with the COPS in order to check the reproducibility of the measurements. Figure 5 show the relative positions of the cross-hair laser, as seen by the two pairs of CCDs, as a function of time. The laser-COPS system was left undisturbed on an optical bench, while the computer read out the peak positions every 20 minutes. The periodic structure, with a 24 hours cycle, displayed by the horizontally oriented CCDs (CCD3 and CCD4), is due to temperature dependent changes in the laser output as described below. The slow systematic increase in the peak position as seen by the same two CCDs comes from very small rotation of the cylindrical rod, of the standard optical support, holding the laser source. The rod is held, by the pressure of a single screw, to the support base, which is firmly fastened to the optical bench. The laser source, in turn, is attached to the rod by the pressure of another single screw.

Sensitivity to Laser Beam Intensity

The regular peak structure seen in the CCD3, CCD4 time measurement of Figure 5 is due to fluctuations in the laser intensity. In order to lower the intensity of the laser diode we resorted to the expedient procedure of lowering the input voltage below the normal operating level. The intensity fluctuations seem to have been caused by sensitivity to temperature changes under that abnormal condition. Figure 6 shows the time variation of the ADC peak height as seen by CCD3. The periodicity of the pattern is precisely 24 hours (72x1200 sec). CCD1 and CCD2, in Figure 5, showed much less sensitivity to the fluctuations of the laser intensity because the horizontal arm of the cross-hair, seen by them, was sharper and better defined than the vertical one.

Considerations on Multi-COPS Alignment

When several COPS are in operation, using the same cross-hair laser, the question of shadowing of a COPS by the one upstream begins to become important. The CCD array sensors are located 8mm away from the edge of the cutout window, and the cross-hair pattern illuminating a given COPS, must come through the cutout window of the preceding COPS. If the separation between the COPS is small, then, as seen in Figure 7, one or more of the CCD arrays might not be fully illuminated. There is enough redundancy in the system, so that one could ignore one of the arrays, and still be able to measure the X-Y coordinates of the beam, and its relative axial rotation. However, it is possible to arrange the window sizes so that the dynamic range is preserved and no loss of redundancy occurs when the detectors can be spaced adequately.

Fast Measurements

Each of the measurements described above consisted of averages of about ten read-outs. That smoothes out oscillations, or any fast (of a few seconds duration) change in relative position between the laser source and the COPS. Single read-out measurements are of course faster, and thus reflect more accurately the instantaneous relative position of the system components.

If one were to use the single read-out measurements then the COPS can determine changes in position at rates better than a few hertz; our prototype board, without any optimization for speed could be read-out and analyzed at the rate of 1.5 Hz. This can be useful in cases where misalignments could be caused by transient movements or oscillations. The reproducibility of the single read-out measurement is better than 1/10 of a pixel.

In our tests we have been able to detect oscillations of about 1 Hz in the relative position between the laser beam and the COPS board. Figure 8 shows the position of the laser peak as seen by the two vertical CCD arrays; the two sequences of partial measurements, taken almost simultaneously every 2/3 sec, track each other very closely. The occasional discrepancy observed in the plot could be attributed to transients faster than the readout time of a single CCD array.

Since we can only observe changes in the relative position, between the laser beam and the COPS board, how can one tell which of the two is moving? The oscillations shown in the two upper sets of data points of Figure 8 actually come from the building, where our laboratory is located, through the laser support. When the laser source was set on a carefully cushioned support the oscillations were very much reduced, as shown by the two lower curves.

Recent Developments.

Just before this work was sent out for publication we tried an important improvement on COPS. We have tested a new orientation for the CCDs, with respect to the laser beam direction. The original orientation was with the CCDs faces pointing towards the laser source; the new orientation has the CCDs facing a direction normal to that of the laser beam. In other words, the laser beam illuminates a CCD from one side. This required the addition of a Lucite prism over the CCD face in order for the cross-hair laser to be seen by the photo-diodes. The vinyl absorber was taped over the Lucite piece, covering the CCD face as well. Preliminary results confirmed the suitability of this new arrangement which will have the following two advantages:

a) the shadowing problem is substantially reduced, since the sensitive region would now lie at the very edge of the cutout window (instead of 8mm outside as in the present COPS); and

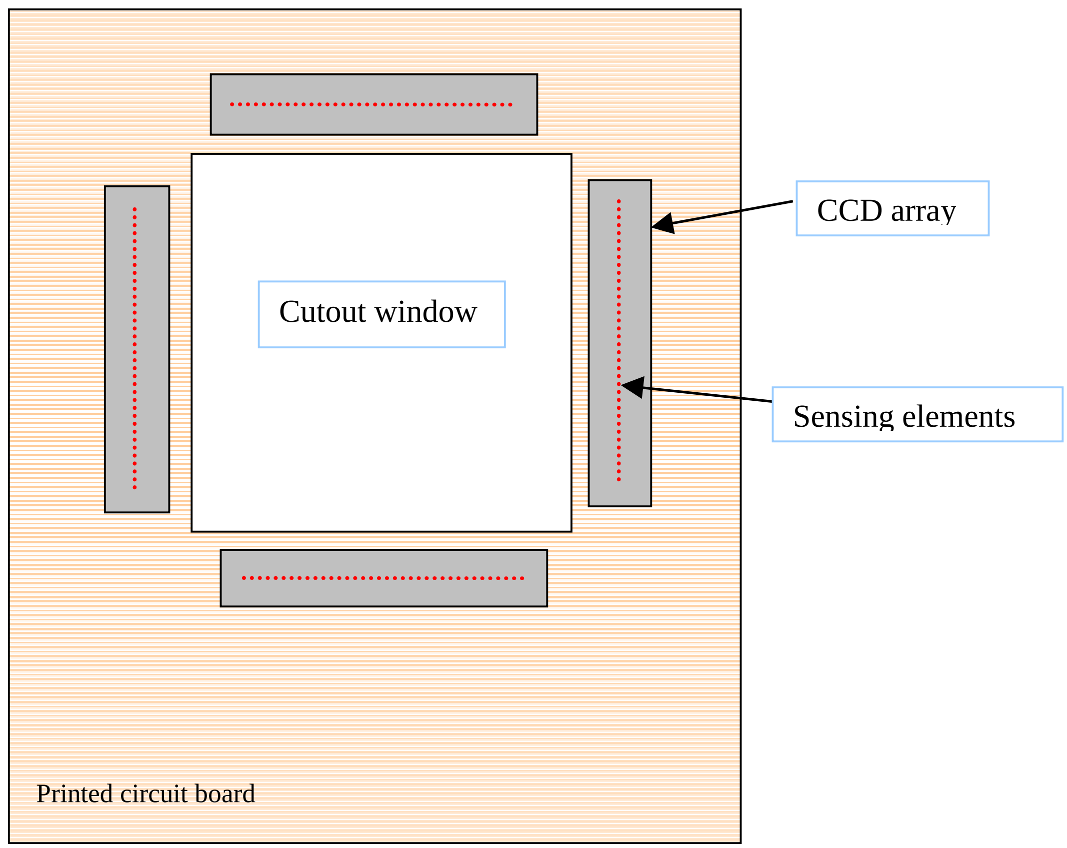
b) The new COPS is reversible, in the sense that it can work with the laser beam coming from either the front or the back, of the p.c. board, or both.

The tests have been done on a single CCD, which was still attached to the p.c. board in the old way. Suitable prototypes will be constructed shortly and more detailed tests will be performed. Figure 9 shows the beam profile taken with the laser line hitting the modified CCD array sideways, first from the right and then from the left.

Conclusions

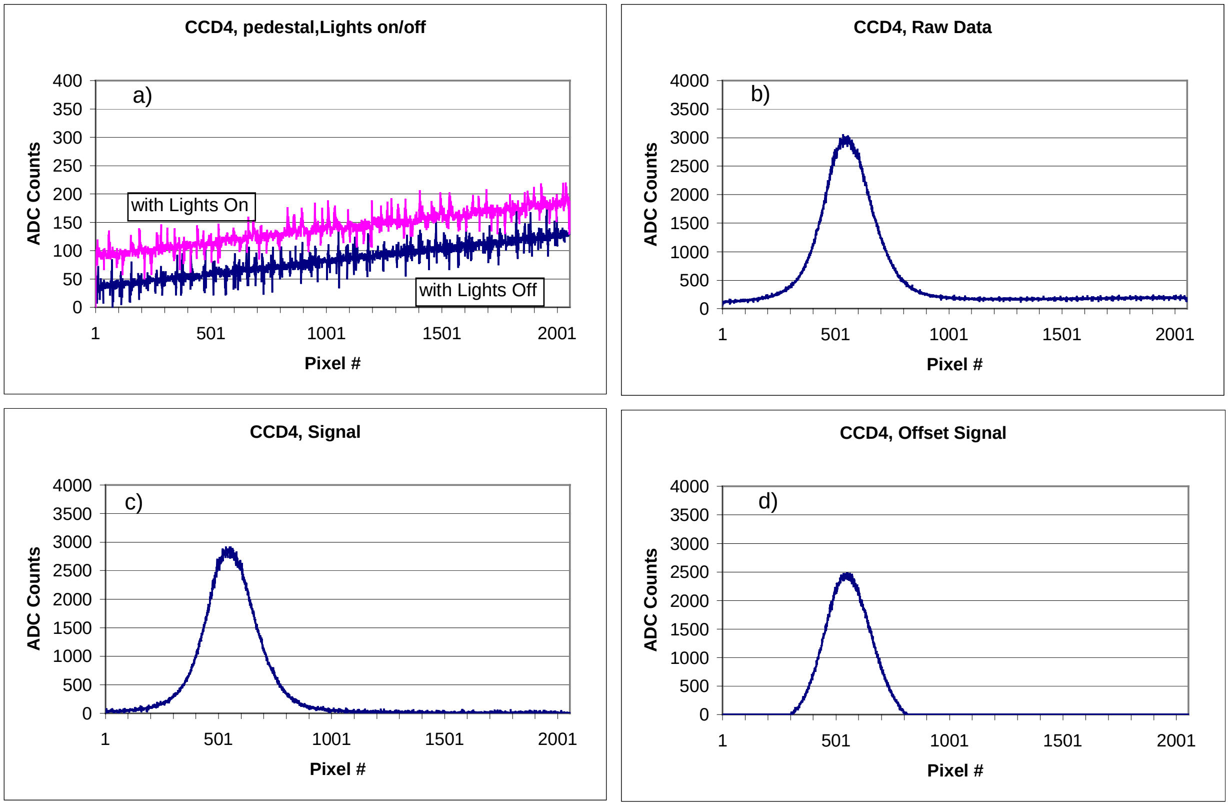
We have tested a first prototype of COPS, a high precision optical position sensor using mass-produced CCD arrays, with a laser diode with cross-hair generator. One of COPS main features is its virtual transparency, which allows the simultaneous measurement of several component positions using a single reference laser beam. Results of the linearity and stability checks performed on it show that precision of a few microns can be easily achieved. The use of four CCD arrays, instead of the two really necessary, gives COPS the additional capability of measuring axial rotations with precision better than 0.1 mrad. Preliminary results obtained with an improved design point the way to further development of COPS.

List of Figures


CCD array
Cutout window
Sensing elements
Printed circuit board

COPS

Fig. 1



CCD4, pedestal,Lights on/off
a)
with Lights On
with Lights Off
ADC Counts
Pixel #
CCD4, Raw Data
b)
ADC Counts
Pixel #
CCD4, Signal
c)
ADC Counts
Pixel #
CCD4, Offset Signal
d)
ADC Counts
Pixel #

Fig. 2

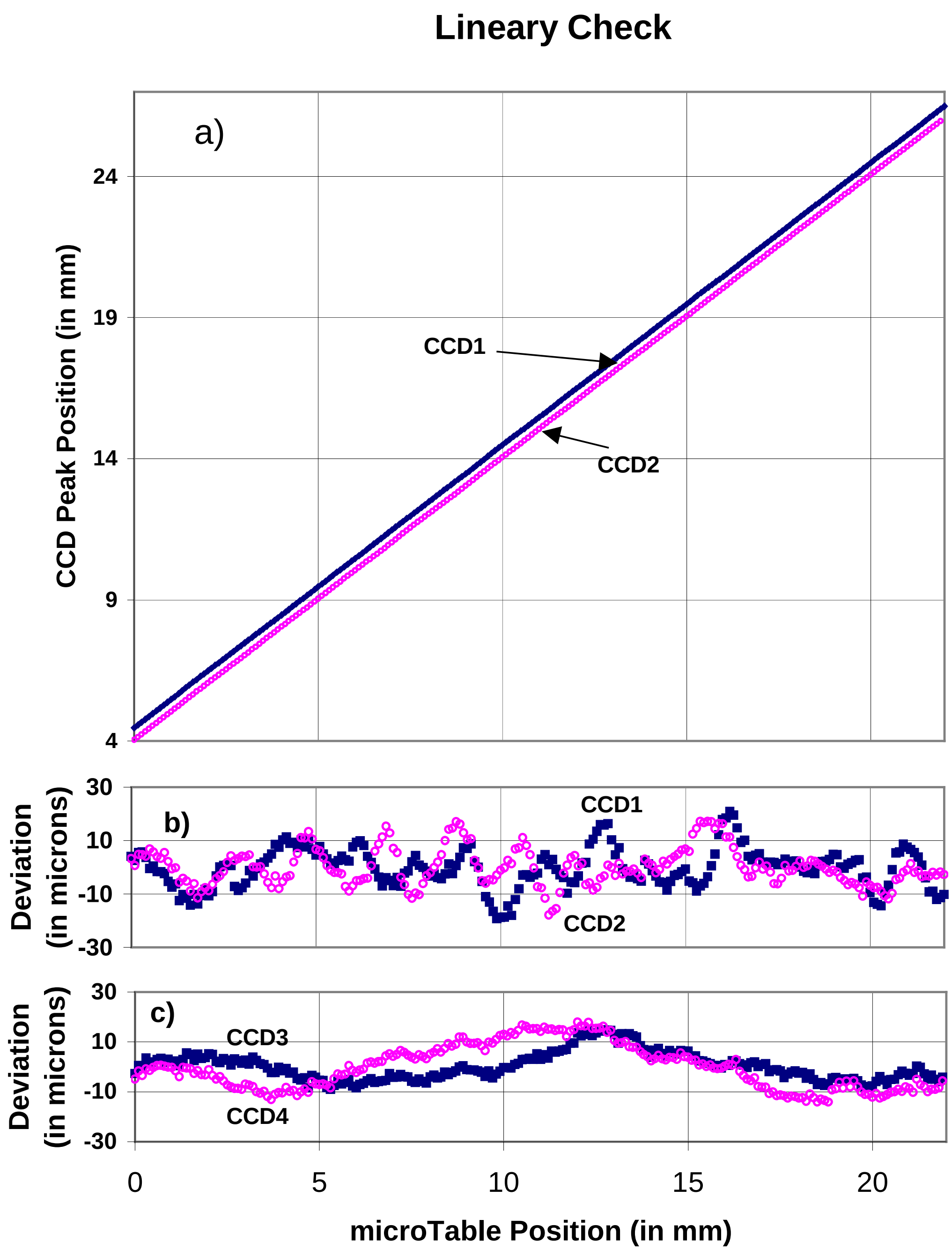

Lineary Check
a)
CCD1
CCD2
CCD Peak Position (in mm)
24
19
14
9
4
b)
CCD1
CCD2
Deviation (in microns)
30
10
-10
-30
c)
CCD3
CCD4
0
5
10
15
20
microTable Position (in mm)

Fig. 3

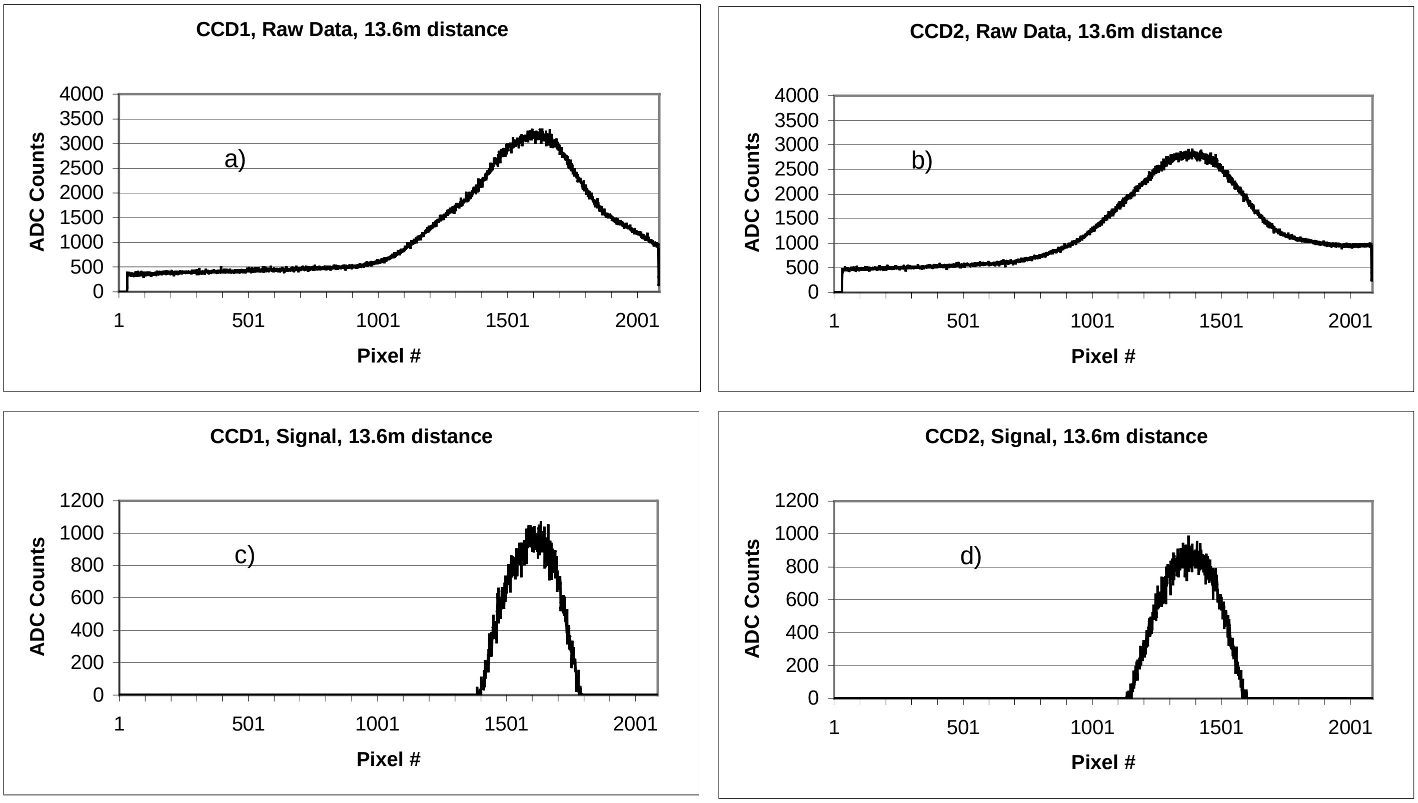

CCD1, Raw Data, 13.6m distance
CCD2, Raw Data, 13.6m distance
CCD1, Signal, 13.6m distance
CCD2, Signal, 13.6m distance
ADC Counts
Pixel #
a)
b)
c)
d)
0
500
1000
1500
2000
2500
3000
3500
4000
200
400
600
800
1200
1
501
1001
1501
2001

Fig. 4

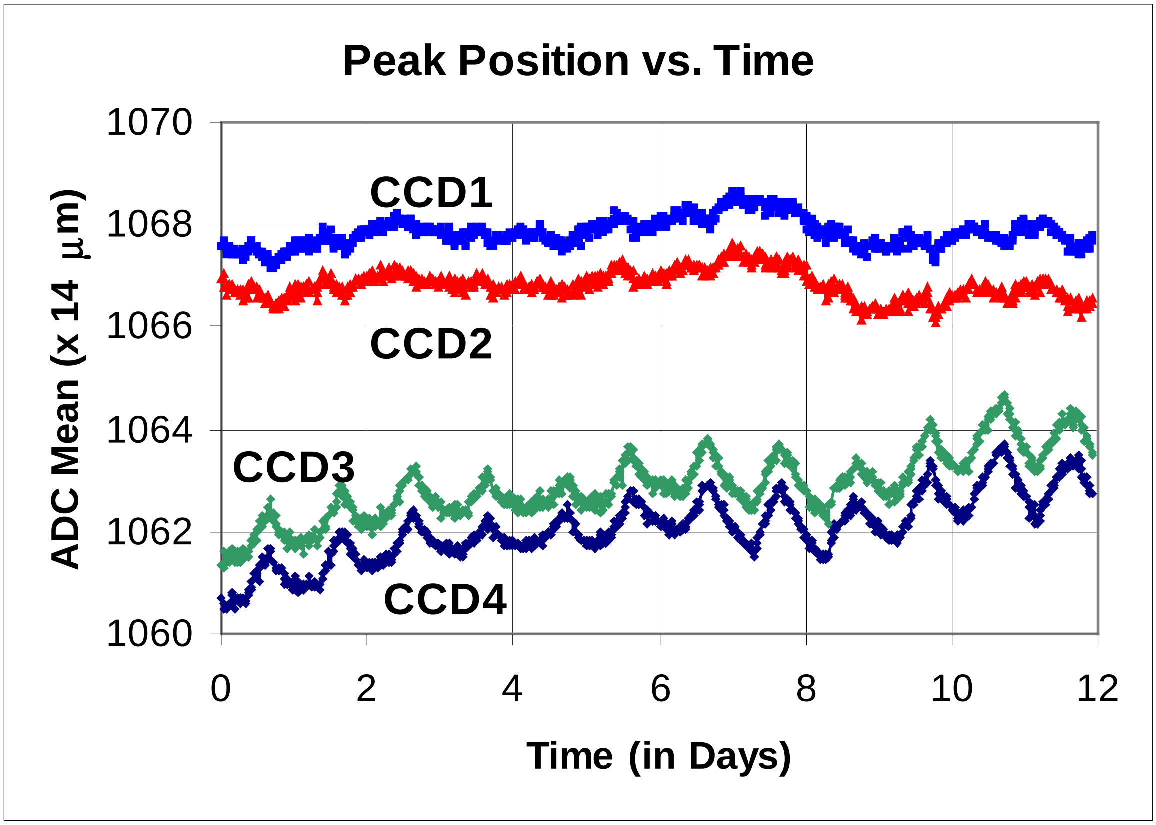
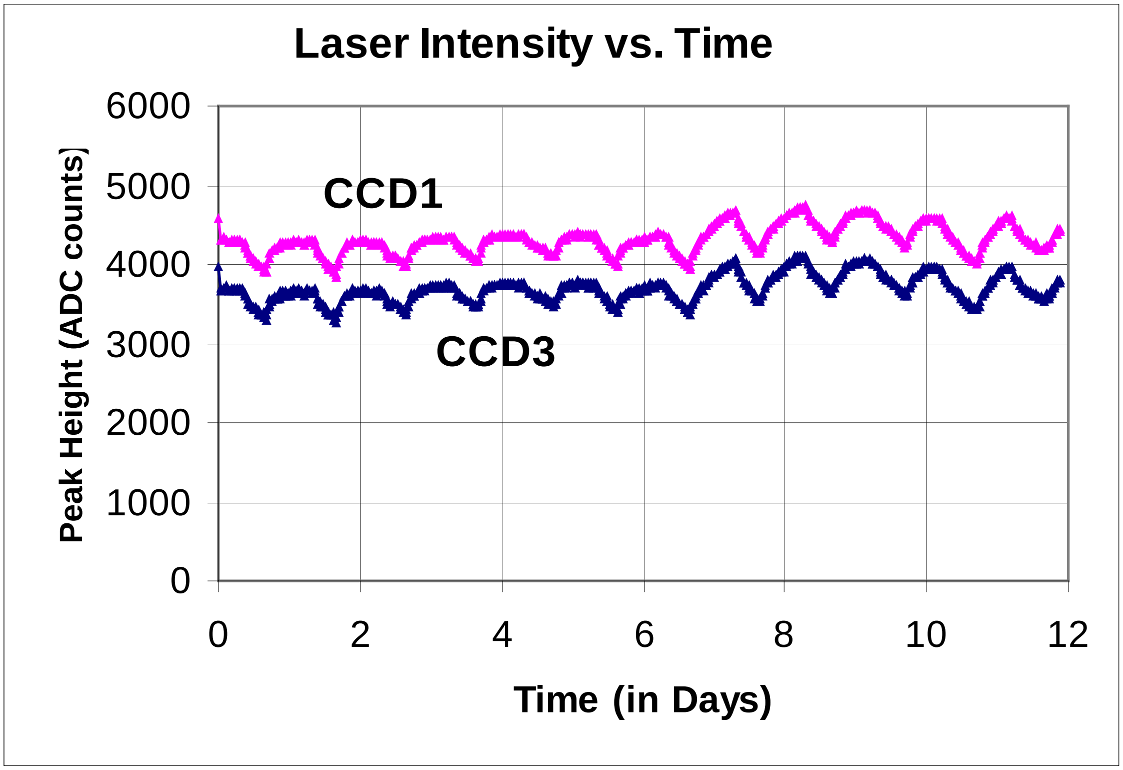

Peak Position vs. Time
1070
1068
1066
1064
1062
1060
ADC Mean (x 14 μm)
CCD1
CCD2
CCD3
CCD4
0
2
4
6
8
10
12
Time (in Days)

Fig. 5



Laser Intensity vs. Time
CCD1
CCD3
Peak Height (ADC counts)
6000
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
12
Time (in Days)

Fig. 6

Schematics of Shadowing Effect in COPS

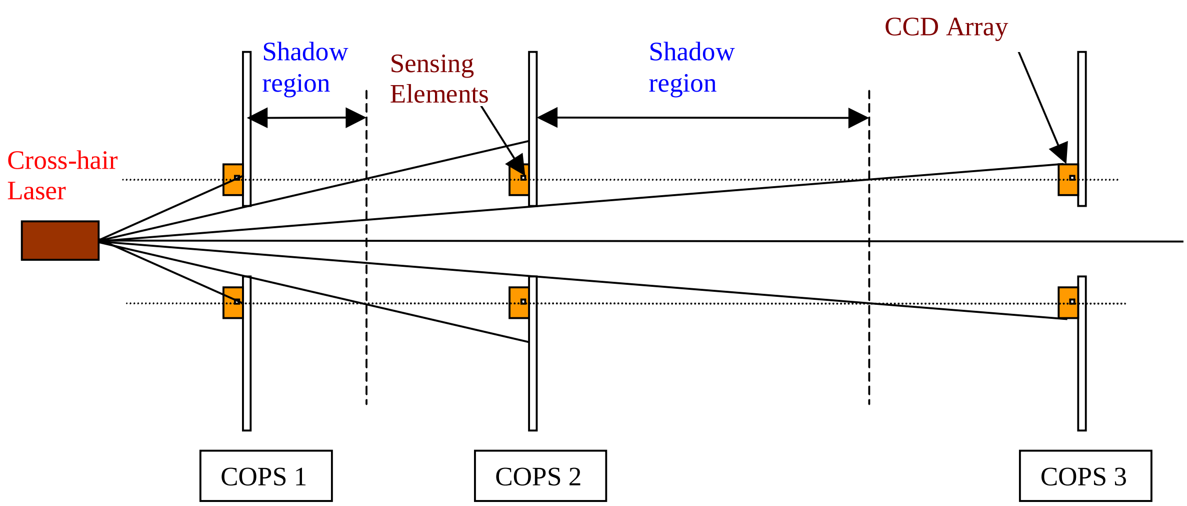
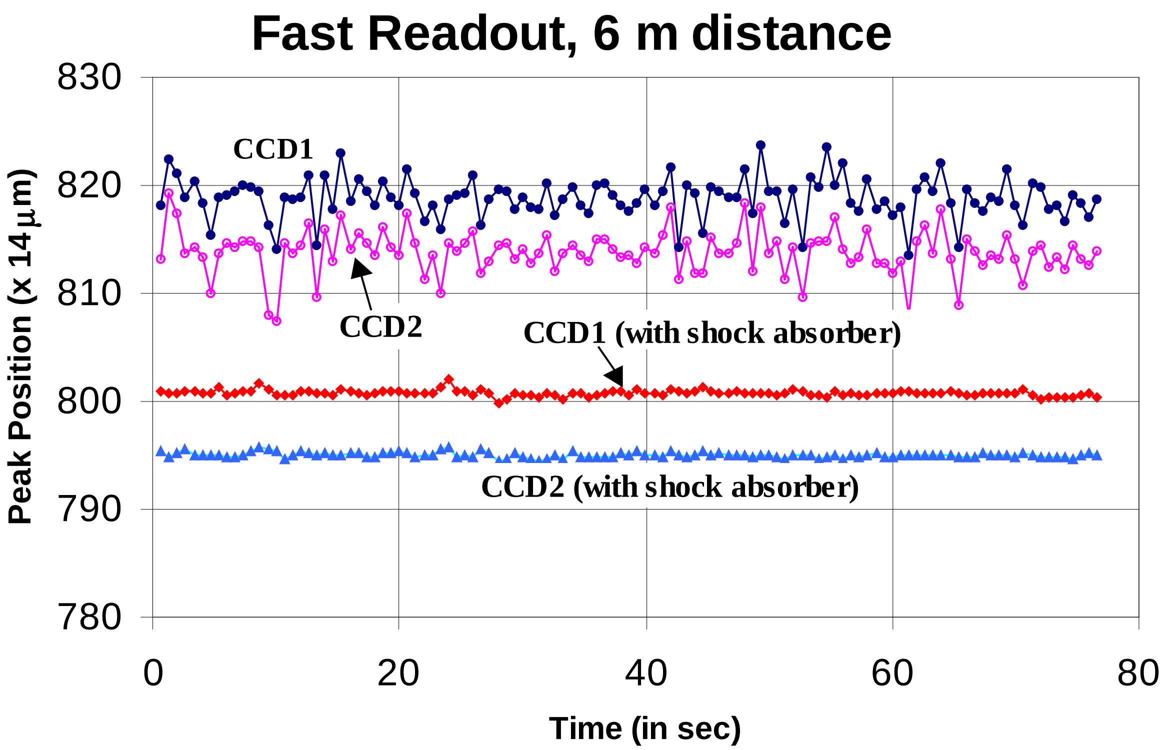


Fig. 7



Fast Readout, 6 m distance
830
820
810
800
790
780
Peak Position (x 14µm)
CCD1
CCD2
CCD1 (with shock absorber)
CCD2 (with shock absorber)
0
20
40
60
80
Time (in sec)

Fig. 8

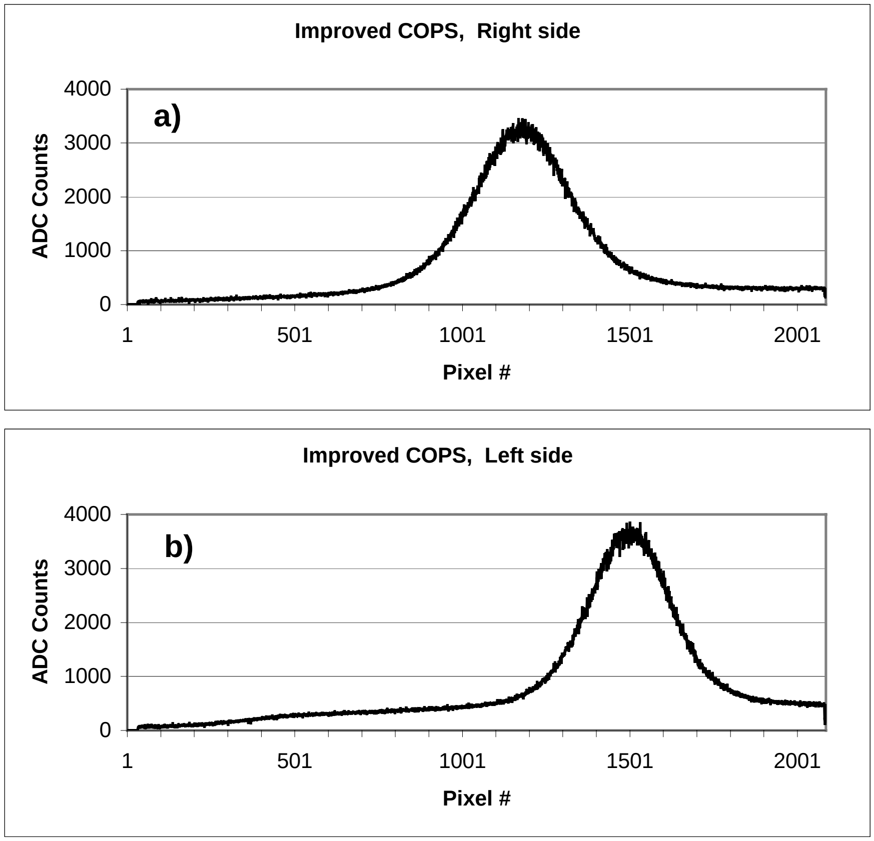

Improved COPS, Right side
a)
ADC Counts
4000
3000
2000
1000
0
1
501
1001
1501
2001
Pixel #
Improved COPS, Left side
b)
ADC Counts
4000
3000
2000
1000
0
1
501
1001
1501
2001
Pixel #

Fig. 9

References

[1] D.P. Eartly, et al. "COPS Position Monitoring System for CMS Endcap Muon Detector", CMS-Note 1996/021

[2] The original idea for COPS was developed by J.C. Gayde and R. Molinero, and presented as "FAST System Concept and Tests at CERN", at a CMS Alignment Meeting on March 7,1995.